

## All-solid-state UV transmitter development for ozone sensing applications

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### Abstract

In this paper, recent progress made in the development of an all-solid-state UV transmitter suitable for ozone sensing applications from space based platforms is discussed. A nonlinear optics based UV setup based on Rotated Image Singly Resonant Twisted Rectangle (RISTRA) optical parametric oscillator (OPO) module was effectively coupled to a diode pumped, single longitudinal mode, conductively cooled, short-pulsed, high-energy Nd:YAG laser operating at 1064 nm with 50 Hz PRF. An estimated 10 mJ/pulse with ~10% conversion efficiency at 320 nm has been demonstrated limited only by the pump pulse spatial profile. The current arrangement has the potential for obtaining greater than 200 mJ/pulse. Previously, using a flash-lamp pumped Nd:YAG laser with round, top-hat profile, up to 24% IR-UV conversion efficiency was achieved with the same UV module. Efforts are underway to increase the IR-UV conversion efficiency of the all solid-state setup by modifying the pump laser spatial profile along with incorporating improved OPO crystals.

### 1. Introduction

NASA is actively engaged in the development of space-based active remote sensing missions using lidar techniques. To develop reliable and robust laser based lidar systems, NASA began the Laser Risk Reduction Program (LRRP) in 2002. Jointly run by Langley Research center (LaRC) and Goddard Space Flight Center, the LRRP is designed to advance laser performances as well as to mitigate associated risks in critical components such as pump diodes for remote sensing applications from space based platforms. The technical objective of LRRP is to develop high-energy, solid-state, conductively cooled and single longitudinal mode 1 micron and 2 micron lasers and appropriate wavelength conversion technologies suitable for four lidar techniques namely altimetry, Doppler, Differential Absorption Lidar (DIAL), and basic backscatter signal strength profiling. The overall goal of LRRP is to advance laser technologies to the point that science mission proposals could be confident of acceptable risk upon selection. The all-solid-state, conductively cooled, compact, high energy UV transmitter technology discussed here enables the precise, high-resolution measurement of atmospheric ozone from space based platforms called for by the Decadal Survey [1].

For ozone profiling from space based platforms, efficient 1-micron to UV wavelength conversion technology to generate tunable, pulsed UV wavelengths of 308 nm and 320 nm is being pursued. The high energy low repetition rate UV transmitter is being developed for atmospheric ozone profiling using differential absorption lidar (DIAL) technique suitable from polar low earth orbits for strong daylight conditions. Based on modeling and simulation studies, it was decided to generate at least 200 mJ per module with low pulse repetition rates at UV wavelengths.

The current UV transmitter configuration uses a pulse-injection-seeded image-rotating nanosecond optical parametric oscillator (OPO) that generates a near-IR signal wavelength [2-4]. The nonlinear optics arrangement consists of an OPO, known as Rotated Image Singly Resonant Twisted Rectangle (RISTRA) module and a sum frequency generation (SFG) assembly. UV wavelengths are obtained by subsequent sum-frequency generation (SFG), where the energies of the signal and pump photons are combined inside the OPO cavity. Initially, the 532 nm wavelength is generated from 1064 nm wavelength Nd:YAG laser via second harmonic generation (SHG). The scheme for obtaining 320 nm is to mix the 803 nm wavelength with 532 nm via SFG. Similarly, mixing of 731.5 nm wavelength with 532 nm yields 308 nm. The 803 nm and 731.5 nm wavelengths are obtained by a 532 nm pumped OPO module. Two RISTRA OPOs are used to obtain stable and single mode 803 nm. A small or low energy RISTRA OPO that is locked by Pound-Drever-Hall (PDH) technique and seeded by New Focus tunable diode laser operating at 803 nm. The big or high energy RISTRA OPO that is pulse seeded from the small OPO and locked by energy stabilization technique. For SFG there are two common configurations; extra-cavity, where an SFG crystal lies outside the OPO cavity, and intra-cavity, where the SFG crystal is inside the cavity. Intra-

cavity SFG (IC-SFG) obtains higher conversion efficiency in a smaller volume while extra-cavity SFG usually generates higher pulse energies.

## 2. UV transmitter based on flash lamp pumped Nd:YAG laser

The viability of the above scheme to obtain ~200 mJ/pulse at 320 nm UV wavelength has been established using a flash lamp pumped Nd:YAG laser under laboratory conditions. So far, the RISTRA OPO has demonstrated ~90% pump depletion and subsequently, up to 24% optical conversion efficiency with stable mode quality. The RISTRA configuration has demonstrated to provide enhanced output beam quality. .

We designed and tested two different configurations for nanosecond non-harmonic ultra-violet (UV) generation using a flash-lamp pumped, 10 Hz PRF Nd:YAG laser. The two configurations were (1) extra-cavity, where the sum frequency generation (SFG) crystal is outside the optical parametric oscillator (OPO) cavity, and (2) intra-cavity, where the SFG crystal is inside the OPO cavity. For the extra-cavity configuration, we generated approximately 190 mJ at 320 nm with IR to UV (1064 nm to 320 nm) optical conversion efficiency of 21%. For the intra-cavity configuration we generated approximately 160 mJ at 320 nm with 1064 nm to 320 nm with an optical conversion efficiency of 24%. The two configurations used a RISTRA OPO pumped by the 532 nm second harmonic of Nd:YAG laser to generate an 803 nm signal. The signal was subsequently summed with additional 532 nm light to generate UV at 320 nm. The technique is general and can access other UV wavelengths by selecting a different signal wavelength for the OPO such as 731.5 nm wavelength for obtaining 308 nm..

The key component of our scheme is an image rotating OPO developed at Sandia National Laboratories known by the acronym RISTRA, denoting rotated-image singly-resonant twisted rectangle [5]. The RISTRA is comprised of an assembly that is compact, mechanically robust, and quasi-monolithic and is illustrated in Figure 1. Owing to its nonplanar geometry it requires no cavity-mirror tilt adjustments and is therefore ideally suited for deployment in space- and resource-constrained environments such as airborne or satellite platforms. This RISTRA cavity was selected over traditional planar cavities because image rotation can produce near diffraction limited beams even when the cavity Fresnel number is very large. This capability allows use of large diameter beams while maintaining pump, signal, and UV fluences  $\leq 1\text{J/cm}^2$ . Low fluence places less stress on crystals and optical coatings, thus reducing the risk of system failure due to optical damage.

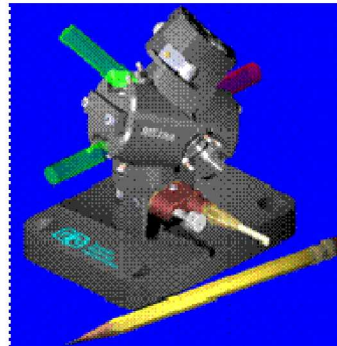
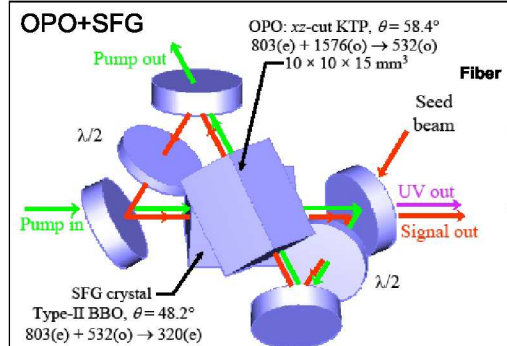


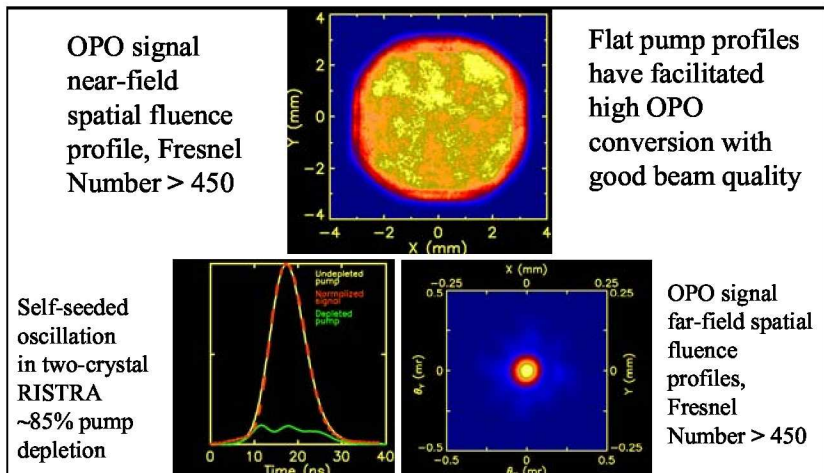
Figure 1. RISTRA OPO configuration. Left: RISTRA OPO with Intracavity SFG. Right: Compact RISTRA assembly in use.

Figure 2 illustrates the performance of the flash lamp pumped Nd:YAG laser based UV converter module.

High efficiency SFG requires single frequency oscillation, and this was achieved by pulse injection seeding the

OPO at 803 nm. Pulsed injection seeding, rather than traditional cw seeding, was used to reduce the build-up time to near zero so that the signal's temporal profile matched that of the pump laser to maximize SFG efficiently. In addition, the pump laser beam, and the pulsed seed beam, had high quality flat-topped spatial profiles to further enhance the overall conversion efficiency.

Figure 2: Illustration of results accomplished with a flash lamp pumped Nd:YAG laser at 320 nm.





### 3. All solid-state UV transmitter

A high energy diode pumped Nd:YAG laser providing up to 1.1 J/pulse at 50 Hz PRF and 22 ns pulsewidth was developed [6]. Following successful demonstration of the UV technique using a flash lamp pumped Nd:YAG laser, the UV converter assembly was coupled to the diode pumped Nd:YAG laser via SHG setup as illustrated in Figure 3.

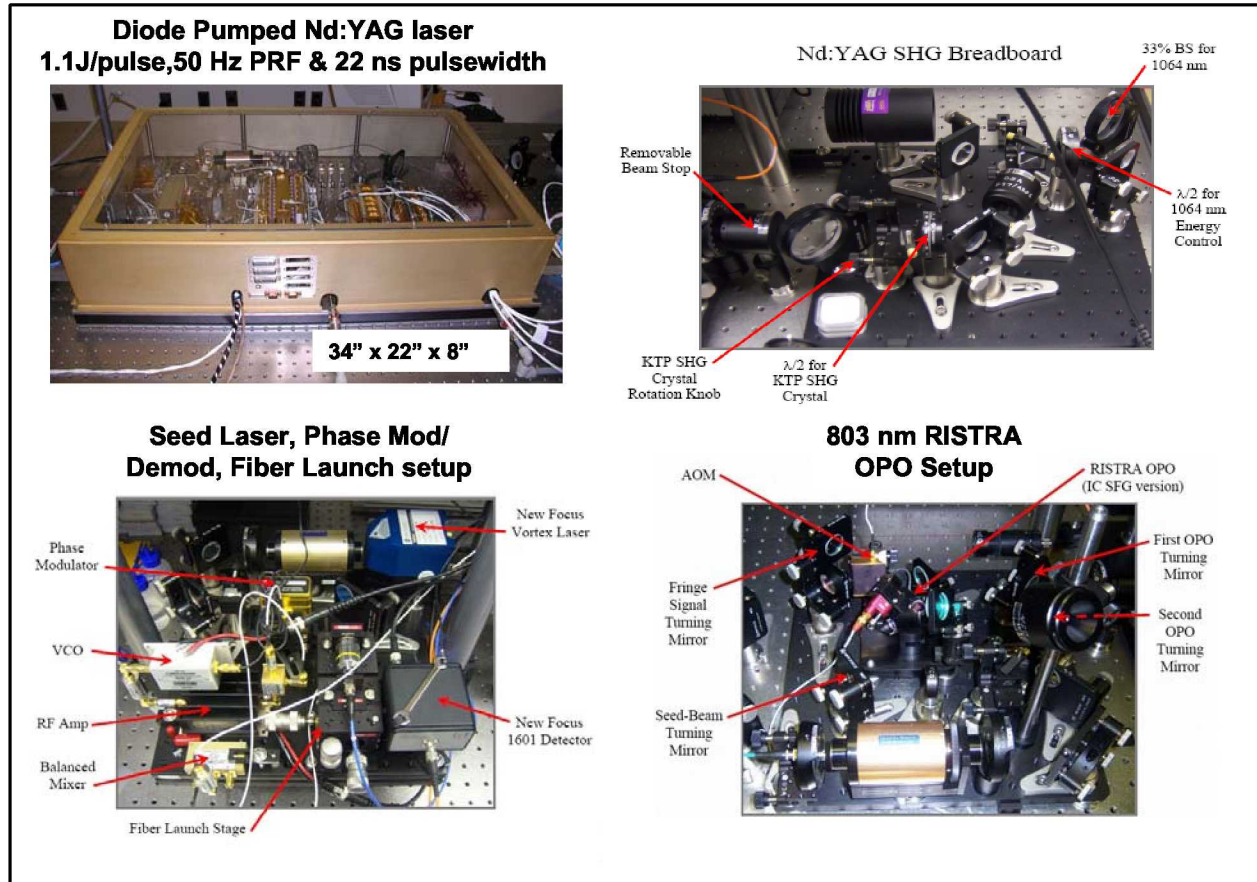


Figure 3. The all-solid-state UV transmitter set up. Shown in this illustration, pump laser (Top left), SHG set up (Top right), Seed laser assembly (Bottom left) and RISTRA based OPO breadboard (bottom right).

The diode pumped Nd:YAG laser configuration consisted of a ring oscillator generating 50 mJ/pulse with two stages of dual amplifiers. At the end of first stage, ~300 mJ/pulse was obtained. In the second stage, ~700 mJ/pulse and ~1.1 J/pulse were achieved at the end of each amplifier module. The pulsewidth slightly varied after each amplification stage and was 22 ns at the final amplifier module. The PRF of the current configuration was 50 Hz with potential for operation up to 100 Hz limited primarily by the drive electronics. Greater than 7% wall plug efficiency was obtained. The output spatial profile of this high energy pump laser was slightly elliptical with nearly Gaussian contours with structures along x and y directions. The  $M^2$  was measured to be ~2.5 at 1.05 J/pulse.

Using a xy-cut Type II KTP crystal, the 532 nm wavelength was obtained via SHG with greater than 82%. Greater than 10 mJ/pulse of UV at 320 nm with 300 mJ/pulse 1064 nm pump energy was obtained yielding IR-UV conversion efficiency of ~10%. The conversion efficiency was limited by non-optimal output spatial profile. The astigmatic output beam from the beam provided reduced overlap inside the nonlinear crystal of RISTRA module primarily limited the conversion efficiency. Due to image rotation, the RISTRA OPO requires round, top hat profile for efficient optical conversion. The pump energy was not increased beyond 300 mJ/pulse at 1064 nm due to potential crystal damage that

could occur due to beam non-uniformity. To optimize nonlinear conversion, several schemes that are being implemented are discussed in the following section.

#### 4. Ongoing work

The overall goal is to develop a viable high energy, field-portable UV transmitter technology suitable for aircraft integration with traceability to a fully hardened spaceborne payload. Significant enhancements in output energy, conversion efficiency, and reliability is anticipated to be achieved by utilizing tailored Nd:YAG laser pump beam with a round flat top spatial profile coupled with following modifications to our current intra-cavity operational scheme: (a) eliminate two-photon absorptive heating effects using BiBO or LBO crystals, (b) redesign image-rotating OPO assembly to enhance cooling of crystals and reduce package size, and (c) incorporate a DFB laser as the frequency-reference for pulse-injection seeding scheme to reduce size, complexity, and power consumption of the RF electronics for frequency stabilization. The proposed effort internal cavity SFG (IC-SFG), as illustrated in Figure 4, is expected to improve nonlinear conversion efficiency by increasing heat extraction from the OPO cavity and by using crystals with lower UV absorption. It also seeks to improve overall system efficiency by transitioning to diode-pumped laser technology that incorporates pump-beams with flat-topped spatial profiles. An IC-SFG based UV transmitter incorporating these enhancements can be packaged into a compact, modular unit with high wall-plug efficiency that is well suited to resource constrained environments. Reduced complexity coupled with the simple configuration of IC-SFG eliminates the need for an external optical path with angle-sensitive nonlinear mixing crystals. For these reasons IC-SFG offers the most direct path to reduced cost, size, volume, mass, and development time, and with higher conversion efficiency it also reduces the power-aperture product. Therefore based on performance of IC-SFG configuration, it is planned to develop a transceiver where two separate IC-SFG OPO assemblies provide two DIAL UV wavelengths.

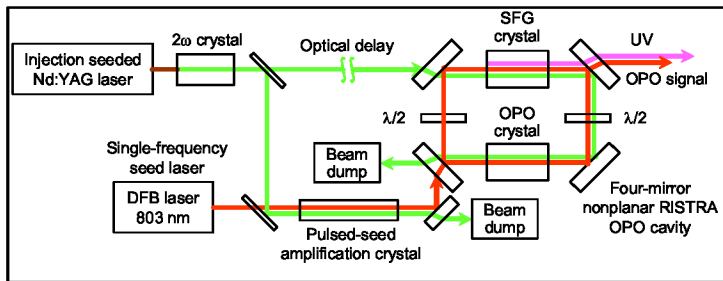


Figure 4. The IC-SFG system with four-mirror nonplanar RISTRA OPO cavity for generating UV wavelengths for ozone DIAL.

#### 5. Summary and Conclusions

We have demonstrated an all solid-state UV transmitter operational at 320 nm based on nonlinear optics arrangement that is coupled to a high energy diode pumped Nd:YAG laser. Up to 10 % conversion

efficiency has been accomplished limited only by the beam quality of the pump laser. Efforts are underway to optimize the pump beam profile and enhance RISTRA OPO performance. A round, top-hat spatial fluence profile instead of current elliptical beam is anticipated to provide greater than 24% IR to UV conversion efficiency.

#### 6. References

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